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Flavor tagging TeV jets for physics beyond the Standard Model

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Abstract. We present a new scheme for tagging boosted heavy flavor jets called "μ_x tagging." At the LHC, the primary method to tag b-jets relies on tracking their charged constituents. However, when highly boosted, track-based b-tags lose efficiency, and the probability to mistag light jets rises dramatically. Using muons from B hadron decay and defining a particular combination "x" of angular information and boost estimation, we find fairly flat efficiencies to tag b-jets, c-jets, light-quark jets, and light-heavy jets (containing B hadrons from gluon splitting) of $\epsilon_b = 14\%$, $\epsilon_c = 6.5\%$, $\epsilon_{\text{light-light}} = 0.1\%$, and $\epsilon_{\text{light-heavy}} = 0.5\%$, respectively. We demonstrate the usefulness of this new scheme by showing the reach for discovery of a leptophobic $Z' \to b\bar{b}$ in the dijet channel.

1 Introduction

As searches for W' and Z' bosons at the CERN Large Hadron Collider (LHC) shift to TeV-scale energies, observation of their decay products becomes challenging. Observation of dijet resonances above QCD background is hampered by falling b-tagging efficiencies (28–15% around 1–2 TeV) and large light-jet fake rates of 1–2% [1]. In addition to the low purity ($\epsilon_{\text{fake}}/\epsilon_b \sim 1/10$), large uncertainties in the tagging efficiencies affect the mass limits; e.g., the ATLAS b-tag uncertainty is 35% for $p_T > 500$ GeV [2]. In order to discover multi-TeV physics beyond the Standard Model (BSM), we need a better b tag with good efficiency and purity.

At this conference, we presented a new method for flavor tagging at TeV-scale energies called "μ_x boosted-bottom-jet tagging" [3]. This method is derived from kinematic first principles, and provides both a well-determined 14% efficiency for b-tagging, and a factor of 10 improvement in fake rejection over existing tags ($\epsilon_{\text{fake}}/\epsilon_b \sim 1/100$). In Sec. 2 we summarize the algorithm and cuts for the μ_x tag, show why it works, and plot its transverse momentum p_T- and pseudorapidity η-dependent efficiencies. In Sec. 3 we briefly describe the application of μ_x boosted-b tagging to an analysis for discovery of a leptophobic $Z' \to b\bar{b}$. We summarize our results in Sec. 4.

2 μ_x boosted-b tag

Consider a jet containing a semi-muonic decay of a B hadron. In the center-of-momentum (CM) frame, the muon is emitted with a speed $\beta_{\mu,\text{cm}}$ and at an angle θ_{cm} with respect to the beam axis (see

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Fig. 1). In the lab frame, the boost γ_B of the B hadron compresses its decay products into a narrow subjet at high energy. We define a lab frame observable

$$x \equiv \gamma_B \tan\theta_{\rm lab} = \frac{\sin\theta_{\rm cm}}{\kappa + \cos\theta_{\rm cm}}, \tag{1}$$

where $\kappa \equiv \beta_B/\beta_{\mu,\rm cm}$.

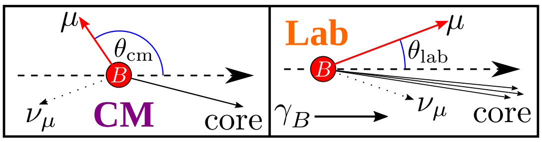

Figure 1. Nomenclature for the center-of-momentum frame and boosted lab frame.

While κ is unobservable, for sufficiently boosted B hadrons ($\gamma_B \gg \gamma_{\mu,\rm cm} \geq 3$) the lab frame distribution of the muon count N vs. x is effectively independent of κ,

$$\frac{dN}{dx} \approx \frac{2x}{(x^2+1)^2}. \tag{2}$$

This leads to a universal shape in x for highly boosted jets containing B hadrons. Using this shape we define the μ_x boosted-b tag as a cut on two variables: We capture 90% of muons from B decay by demanding $x < 3$. To further isolate b decays, we note the hard fragmentation function for b quarks leads to the B hadron subjet carrying a large fraction $f_{\rm subjet}$ of the total jet momentum. Hence, we demand

$$f_{\rm subjet} \equiv \frac{p_{T\,\rm subjet}}{p_{T\,\rm jet}} \geq 0.5. \tag{3}$$

There are two challenges in applying the μ_x tag to real events: we must identify the correct decay remnant of the B hadron to reconstruct its four-vector $p_{\rm subjet}$, and we must deal with the missing muon neutrino. Most of the neutrino energy in the lab frame comes from the boost, so we use the measured four-vector of the muon as a proxy $p_\nu = p_\mu > 10$ GeV. In order to find the non-leptonic remnant "core" of the subjet, we need a more sophisticated algorithm.

In order to reconstruct the boosted subjet we first cluster the jet using the anti-k_T algorithm with a $R = 0.4$. We then search for the core (generally the charm hadron remnant) by reclustering the muon and calorimeter towers with total jet energy fraction $f^{\rm min}_{\rm tower} > 0.05$ using a smaller $R_{\rm core} = 0.04$. We assume $m_{\rm core} = 2$ GeV (a typical charm hadron mass), and identify the "correct" core as the one which comes closest to $\sqrt{p^2_{\rm subjet}} = 5.3$ GeV. Since mismeasurements smear out the reconstructed energy of the subjet, if $m_{\rm subjet} > 12$ GeV we constrain the subjet mass to be 12 GeV. The parameters of the μ_x tag are summarized in Table 1.

Table 1. A summary of parameters chosen for μ_x boosted bottom jet tagging.

$\boldsymbol{R}$	0.4	$\boldsymbol{m_{\rm core}}$	2 GeV	$\boldsymbol{p^{\rm min}_{T\mu}}$	10 GeV
$\boldsymbol{R_{\rm core}}$	0.04	$\boldsymbol{m_B}$	5.3 GeV	$\boldsymbol{x_{\rm max}}$	3 ($x_{90\%}$)
$\boldsymbol{f^{\rm min}_{\rm tower}}$	0.05	$\boldsymbol{m^{\rm max}_{\rm subjet}}$	12 GeV	$\boldsymbol{f^{\rm min}_{\rm subjet}}$	0.5

In spite of its non-trivial reconstruction, x is effectively a dynamic angular cut on the muon. Defining ξ, the lab frame angle between the muon and the core, it is possible to calculate $\xi_{\rm max}$, the maximum μ-to-core angle which produces $x \leq 3$. For "soft" muons ($E_\mu \ll E_{\text{core}}/18$), this angular cut is relatively tight

$$\xi_{\text{max}}^{\text{soft}} \approx 3\frac{m_{\text{core}}}{E_{\text{core}}}. \tag{4}$$

Once the muons become "hard" ($E_\mu \geq E_{\text{core}}/18$), the cut loosens significantly

$$\xi_{\text{max}}^{\text{hard}} \approx 3\frac{m_{\text{subjet}}^{\text{max}}}{E_{\text{core}}}. \tag{5}$$

While the transition between these limits depends explicitly on the muon's p_T, this dependence is small until just below the hard threshold. Thus, not only is x a *smart* angular cut — scaling with the energy of the core — it is a *dual* angular cut; tight for soft muons, looser for hard muons, and sensitive to the p_T resolution of the muon system only within the narrow transition region.

The separation of reconstructed b jets from light-quark-initiated jets can be seen in Fig. 2. Bottom jets (b-quarks hadronized as B hadrons) above 500 GeV produce large f_{subjet} and $x \sim 0.8$. Light jets (mostly π and K) produce either incompatible values of $x > 3$, or random subjet recombinations that lead to small f_{subjet}. A small fraction of b jets is not well-reconstructed (represented by the low-f_{subjet} tail), but it has little effect on the total efficiency.

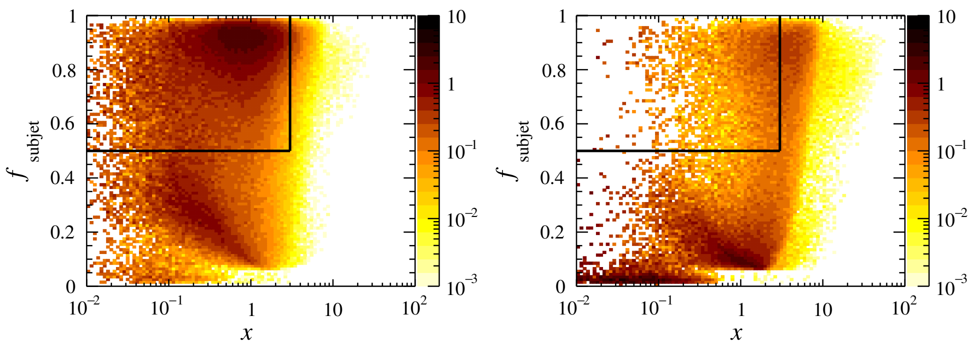

Figure 2. Density of reconstructed candidate tags with $\mu = 40$ pileup events as a function of f_{subjet} vs. x for (left) bottom and (right) light-quark-initiated jets.

We extract the standalone μ_x tagging efficiencies using PYTHIA 8.210 [4, 5] fed into an ATLAS-like version of DELPHES 3.2 [1], and a custom μ_x tagging module `MuXboostedBTagging` (available on GitHub [6]). In Fig. 3 we show separate efficiencies as a function of p_T and η for bottom jets, charm jets, light-light jets (where the muon came from a light-flavor hadron), and light-heavy jets (where a gluon split to $b\bar{b}/c\bar{c}$ — producing heavy-flavor hadrons in the final state). The kinematic nature of the tagging variables leads to fairly flat efficiencies in pseudorapidity, and when $p_T > 500$ GeV. The exception is the η distribution for B hadrons from gluon splitting. This leads to the intriguing possibility that the $g \to b\bar{b}$ contribution to jets in the Monte Carlo could be calibrated using the rapidity dependence of these highly-boosted jets.

3 A search for leptophobic $Z' \to b\bar{b}$

Very massive Z' bosons are expected to exist in many BSM models. We test the μ_x boosted-bottom tag by examining the reach at a 13 TeV LHC for a leptophobic Z' decaying to $b\bar{b}$ or $c\bar{c}$. For this study

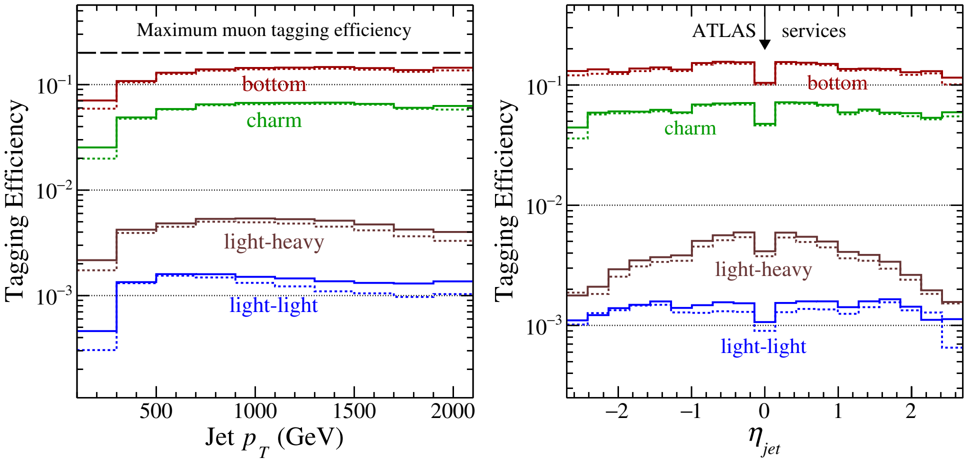

Figure 3. μ_x tagging efficiency vs. (left) jet p_T and (right) $\eta_{\rm jet}$. Solid (dashed) lines include $\mu = 0$ (40) pileup events.

we choose a $U(1)'_B$ Lagrange density

$$\mathscr{L} = \frac{g_B}{6} Z'_{B\mu} \bar{q} \gamma^\mu q, \tag{6}$$

with a flavor-independent coupling to quarks [7, 8].

We simulate the signal and backgrounds using a MLM-matched MadEvent sample [9] and CT14llo PDFs [10] fed through PYTHIA into DELPHES. In addition to demanding one or two μ_x tags (as defined in Sec. 2), we require $|\eta_j| < 2.7$, and $\Delta\eta_{jj} < 1.5$. We reconstruct a dijet mass out of the two leading-p_T jets, and look for a resonance in the mass window $[0.85, 1.25] \times M_{Z'_B}$.

The results for 5σ discovery of this leptophobic Z' are shown in Fig. 4 for a two-tag, and one-tag inclusive sample, compared to current exclusion limits from Ref. [7]. In 100 fb^{-1} of integrated luminosity at 13 TeV, a two b-tag analysis could discover a Z' of 3 TeV if the universal coupling $g_B \sim 2.5$. For this particular model, the single-tag inclusive search would be more effective — allowing for discovery up to nearly 1 TeV above current mass limits. Should a discovery not be made, the two-tag search (not shown) would set a 95% C.L. exclusion comparable to the one-tag discovery reach; while the one-tag search would set a 95% C.L. exclusion that can access g_B couplings a factor of 2 smaller than current limits, and masses up to 2 TeV higher.

4 Conclusions

In this paper we discuss the new μ_x boosted-bottom-jet tag. Combining angular information x from B hadron decay with jet substructure $f_{\rm subjet}$ in TeV-scale jets allows for tagging efficiencies of $\epsilon_b = 14\%$, $\epsilon_c = 6.5\%$, $\epsilon_{\rm light-light} = 0.1\%$, and $\epsilon_{\rm light-heavy} = 0.5\%$, respectively. The results here focused on ATLAS because their standalone non-isolated muon tagging efficiency is publicly available. We expect that if CMS has similar non-isolated muon tagging capability this tag will be just as effective, since it is kinematically driven and not sensitive to fine details of the detector.

When applying the μ_x tag to a search for leptophobic Z' bosons, we find that the reach for discovery at a 13 TeV LHC is about 1 TeV higher than current limits. If a Z' is not found, 95% C.L.

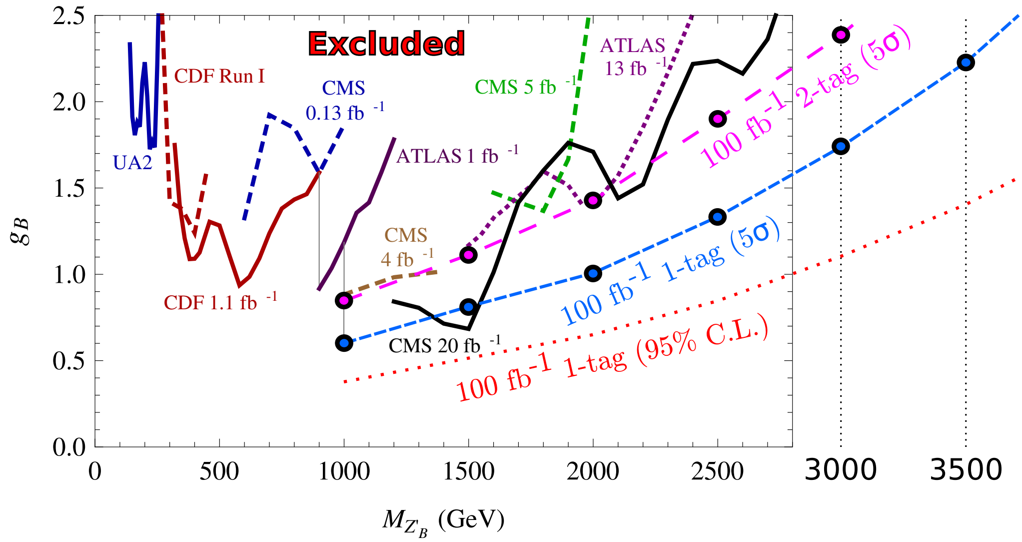

Figure 4. 5σ discovery reach for a leptophobic Z' with universal coupling in the with one or two boosted-b tags at a 13 TeV LHC compared to exclusion limits from Ref. [7]. Also shown is the 95% C.L. exclusion reach of the one-tag analysis.

exclusion limits can be set up to 2 TeV higher, or for g_B couplings a factor of 2 smaller, than the current limits. In addition to $Z' \to b\bar{b}$, the μ_x tag should be of immediate use in the search for $W' \to t\bar{b}$ in the boosted-top and boosted-bottom channel [11] conducted by the ATLAS Collaboration [2].

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References

[1] J. de Favereau *et al.* (DELPHES 3 Collaboration), J. High Energy Phys. **02**, 057 (2014) [arXiv:1307.6346 [hep-ex]].

[2] G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B **743**, 235 (2015) [arXiv:1410.4103 [hep-ex]].

[3] K. Pedersen and Z. Sullivan, arXiv:1511.05990 [hep-ph].

[4] T. Sjostrand, S. Mrenna, and P.Z. Skands, J. High Energy Phys. **05**, 026 (2006) [hep-ph/0603175].

[5] T. Sjostrand, S. Mrenna, and P.Z. Skands, Comput. Phys. Commun. **178**, 852 (2008) [arXiv:0710.3820 [hep-ph]].

[6] K. Pedersen, [https://github.com/keith-pedersen/delphes/tree/MuXboostedBTagging].

[7] B.A. Dobrescu and F. Yu, Phys. Rev. D **88**, 035021 (2013); Erratum: Phys. Rev. D **90**, 079901 (2014) [arXiv:1306.2629 [hep-ph]].

[8] B.A. Dobrescu, arXiv:1506.04435 [hep-ph].
[9] J. Alwall *et al.*, J. High Energy Phys. **07**, 079 (2014) [arXiv:1405.0301 [hep-ph]].
[10] S. Dulat *et al.*, arXiv:1506.07443 [hep-ph].
[11] D. Duffty and Z. Sullivan, Phys. Rev. D **90**, 015031 (2014) [arXiv:1307.1820 [hep-ph]].